Vol.64: e21210187, 2021
https://doi.org/10.1590/1678-4324-2021210187
ISSN 1678-4324 Online Edition

Article - Engineering, Technology and Techniques

Intelligent System for Dispatch Ranking of Generating Units in Thermoelectric Power-Plants

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Editor-in-Chief: Alexandre Rasi Aoki
Associate Editor: Fabio Alessandro Guerra

Received: 2021.03.26; Accepted: 2021.04.09.

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HIGHLIGHTS

- Ranking for dispatching of power generator units.
- Introducing the Modified Analytic Hierarchy Process (MAHP).
- Integration of supervisory systems in thermal power plants.
- Diagnosing problems in generating units.

Abstract: The multicriteria decision-making process is still an open problem, especially when the decision criteria are not numerical or fully outlined. Several numerical, intelligent, or hybrid techniques have been developed, creating contributions to this problem's solution. This paper is another step in this direction. Based on the Modified Analytic Hierarchy Process (MAHP), a methodology for diagnosis and performance analysis is presented for the dispatch ranking of generating units in a thermoelectric plant. The problem is complex because it covers a power plant, where 99 generating units may be dispatched, according to 10 possible evaluation criteria, which should be used together. This article also presents details of the implementation of the sensors necessary to add to the supervisory system existing in the Palmeiras de Goias Thermal Power Plant.

Keywords: dispatching; modified AHP; power plant operation; supervisory system.

INTRODUCTION

Since the last decade, the combination of a low rainfall rate and insufficient investments by the federal government severely impacted Brazil's energy market. The growing electricity demand has prompted the government to implement rationing plans for companies and the population [1]. Also, contingency plans were drawn up by the governmental institutions responsible for the energetic and electric sectors.

As a solution, they consisted of searching for other resources to expand the electrical grid. This fact justifies the incentive to build thermoelectric plants since they are energy sources independent of the water cycle. With this, the Brazilian electrical system becomes more reliable and robust. It is essential to notice that the Brazilian system is one of the few power generation systems globally with its power system based on hydraulic generation. Currently, around 30% of the total Brazilian power generation system comprises thermoelectric plants [2].

These plants need to be available to the National System Operator (ONS) to always produce energy. The ONS is responsible for making the Brazilian system's global optimization, considering economic factors and each plant's reservoir levels. However, it does not consider each generator of the plant's dispatch, observing only the total power. The internal dispatch schedule of each generator is the responsibility of the plant itself. In this way, a new challenge arises for the plants, how to dispatch safely, maintain operational reliability, and preserve the generating units? Thus, an internal dispatch schedule should optimize the power between the generating units [3, 4].

For this to occur, there must be a system capable of performing analyses of the generator units' states available for dispatch, verifying their current operating conditions and their history of maintenance and dispatch. If an impropriate dispatch is made, it will cause increased costs, increased fuel consumption, and it can cause problems to the environment and stress of the facilities. Thus, a system that can improve the process of diagnosis, predictive maintenance, monitoring, and, mainly, the supervision of the start-up of generators would be extremely desirable for all thermal power plants and thermal systems [5].

Then, to mitigate these problems and contribute to a safer operation, this paper presents a computational tool that assists the operator in establishing an order in which generation unit should be dispatched and at what level this dispatch should occur. This tool goes beyond the units' scheduling because it produces some diagnostics of the generating units' performance, computed by several analyses of the generation set. These analyses are based on measurements performed directly and indirectly at various generating units and comparisons with similar generating units.

Based on intelligent systems techniques, this semi-automatic tool works performs its analysis on the operator's demand, which can, before triggering it, according to your will, modify some parameters. This characteristic that allows the modification of parameters makes this tool also used for the generating units' degradation and performance studies.

When triggered, the tool analyzes the supervisory and control system's data and exchanges data with its database. Diagnosis and scheduling occur in some steps that are entirely transparent to the operator and autonomous. Initially, the tool checks the plant generators' current state, investigates of the operation history, and verifies additional information. In possession of the input data, the system verifies the ONS's demand, and through the proposed Modified Analytic Hierarchy Process (MAHP) technique, sorts the dispatch of the units. During this processing, it produces a diagnosis of deviations from the various measurements of each generating unit to itself and an ideal generation unit. Trend curves and tracking measures with deviations are tracked by the tool, and when levels of preset alarms are reached, messages appear on the operator screen. When the tool makes its results available to the operator, he/she may or may not use them in dispatching the generating units. A log file saves all information for possible future checks.

The tool presented in this article is in operation at the Palmeiras de Goias Thermal Power Plant in central Brazil, which consists of 99 generating units of 1.8MW and with a demand of 170MW.

This paper is divided into the following sections. Section II shows the system of supervision and control of the generation, where the entire sensing, supervisory, and database structures are presented. Section III is composed of the mathematical strategies used. Section IV presents the computational methodology applied in developing the generating units' diagnostic device and performance analysis. Section V presents a referring case study in a real power plant.

System of supervision and control of the generation

At the beginning of the project, it was verified that the existing supervision and control system, installed by the manufacturer of the generating units, had only basic measurements. Most of them relate to the oil consumption in the drive and the power generated at its output. Information and intermediate measures of the generating units practically did not exist.

Thus, a supplementary supervision and control system was developed and incorporated into the existing supervisory system so that the two systems currently operate in an integrated manner.

The supplementary supervision and control system was developed using the Palmeiras de Goias Thermal Power Plant characteristics. This system consists of sensors, controllers, communication modules, among other essential equipment. It was also necessary to consider the physical and communication characteristics commonly existing in a thermoelectric generation unit. All equipment and meters have been installed to form an industrial network.

This complementary system's objective is to capture all the essential variables for the preparation of the analyses. The more measures are acquired with high integrity, and the better value is the result produced by the system [6].

The system is equipped with some strategies of self-protection and correction of input data. Still, suppose the integrity at the time of acquisition is not maintained and the measurements performed do not represent the current state of the units' elements. In that case, the results can totally disqualify the control strategy, causing power loss and shutdowns.

The most important items of the sensing network are listed below. In addition to the points mentioned above, the database and the supervisory program are essential parts for the control strategy's functioning, which are addressed in this section.

Network Topology

Figure 1 presents the topology of the developed control network. The PLCs of each generator are connected via an ethernet network to a network switch. It also has ethernet communication and Modbus protocol [7], responsible for recording the information in the database and sending it to the supervisory system. Each element presented in this network and illustrated in Figure 1 is detailed in the sections below.

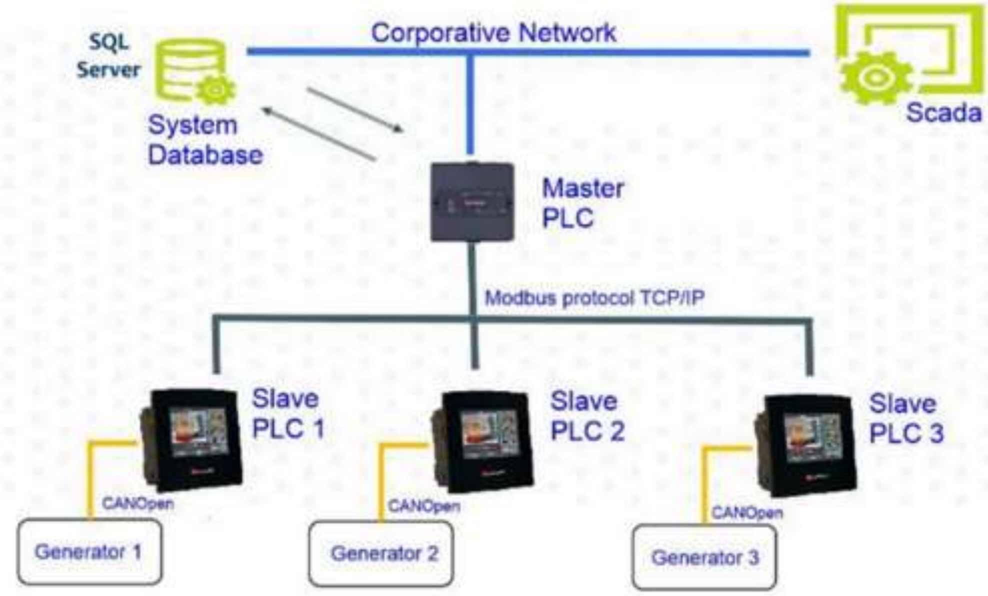


Figure 1. Network topology and main equipment and devices.

Flow Meter

Measurements of generator consumption can be performed through an estimation considering the energy expenditures model of the generator and their mathematical relationships with the power generated. However, to maintain the data's integrity and obtain greater accuracy, the flow meters were installed.

Initially, only 25 generators were connected to the flow meters and the PLC of the Samba line. The Samba PLC is connected to the flow meters and the SAM module, allowing access to other variables of the generating units such as errors, alarms, and momentary indicators.

For technical and economic reasons, the Piusi flow meter, model K400PULSER, was chosen. This equipment's operating principle is based on the aluminum dry contact meter with a Reed Switch-type sensor. The meter has an output signal with the square wave profile, also has a free flow rate of 1 to 30 [L/min], accuracy for plus or minus 0.5%, a weight of 0.51kg, and the dimension is 77mm x 62mm. This meter is installed at the generator fuel system entrance and exit, as shown in Figure 2. Thus, it allows the instantaneous measurement of fuel consumption during the operation of the generating units.

(a) (b)

Figure 2. PIUSI fuel meter placement – entrance side: (a) before installation, and (b) after the installation.

The PLC must have some specific characteristics: small physical size, large processing capacity, low cost, and a man-machine interface. It should also allow communication with the system of acquisition of measures, visualization of local variables, and return of the control strategy, such as ranking and alerts.

The PLC chosen is the SAMBA model, specifically SM35-J-T20 [8], whose manufacturer is Unitronics. Among the CHOSEN PLC features are creating data tables and their export, a library with hundreds of graphics displayed on the touchscreen monitor, and online monitoring of programming logic.

Ethernet Module and CAN Bus Module

The Ethernet module allows you to add a port to the SAMBA PLC and implement TCP/IP communications, such as the MODBUS on TCP, which has the same type of protocol used by the PLC of data concentrator. Some attributes to mention are the transmission speed of 10/100 Mbps and the ability to allow 100m of cables between the module and the switch, an essential feature for installation in a thermal power plant, where the distances are expressive.

The CAN (Controller Area Network) bus protocol allows the exchange of data between microcontrollers and various devices without a host computer's need. It is widely used when it becomes vital to multiplex electrical signals in industrial environments. Protocol actuation occurs when all devices are connected to the same network, and they receive the transmitted message.

The transmitter and receiver with the highest priority receive the message and communicate to the other devices, thus creating a well-structured non-centralized network. This fact is one of the project's main features, as it decentralizes the transmission of data between the Samba PLC and the SAM module. Unitronics manufacture the module chosen, model CAN V100-17-CAN. It is compatible with CAN-Open and UniCAN.

Network Concentrator PLC

Several SAMBA PCLs are connected to the network to acquire data. When the data is accessed individually, the process becomes unproductive, deteriorating one of the project's objectives related to the simultaneous process of data acquisition and analysis. The need to concentrate all these devices on a single piece of equipment led to adopting a network concentrator PLC. It makes the data available for all other equipment and then stores it in the database. This solution aims to simplify the procurement and storage procedure by using only the concentrator PCL. In other words, a single device with Modbus protocol is intended, which should operate independently of the supervisory in the plant, generating autonomy for the solution. The model chosen was Unitronics' USC-B10-B1. The controller's main functionality is remote operation capability, which occurs through a virtual human-machine interface (HMI) installed on a computer.

The network hub PLC requires software for specific program communication functions. For example, the location where the relevant data from the generating units is stored and written to the database. UniLogic software, free and compatible with the PLC defined for this application, was used in this implementation. Figure 3 shows a screen during the programming.

Figure 3. Concentrator PLC programming software.

Network Switch

The network switch allows multiple points of the built network to be concentrated on a single node, making it easier to collect and transmit data. The model chosen was the HP 1820-24G - J9980A, which features excellent network performance, intelligent feature management, and an intuitive interface.

Database

The data obtained by the slave PLCs in the new topology developed and the data resulting from the computational tool need to be archived in a database. In possession of the data, the supervisory can update the main screen with the generators' classification and the specific indicators for each variable of the generating units, alarm screens, graphs with the history of rank, and even as an alternative repository to the analysis program. The data store was generated using the SQL language, which is proper to relational databases.

Tables have a structure and names that can be replicated to all plant generators and those implemented in the computational tool. In this case, the database tables are named GEN_001, GEN_002, and so on. Two table variables have an interesting application, which is E3TimeStamp and FP_Quality. The first indicates the exact moment that the data column was logged into the database. The second shows the connection quality at the time of recording, being 192, the best possible connection quality, and 20 the worst. In this way, it is possible monitoring the integrity of the recorded data.

Supervisory System Software

The supervisory system was designed using the Elipse E3 language. Its purpose is to condense all the information generated by the concentrator PLC and analyze the computational tool, and the necessary data read from the database. There is a concern to present all the data intuitively to the operator and make quick decisions. Figure 4 shows the supervisory system's home screen, where each square represents a plant generator, and each color is used to identify the generator's status. The red color indicates that the generator is not in operation, while the green color indicates the correct operation, and the yellow color suggests that some failure is occurring. The generating units' general ranking is presented in the lower-right corner, dividing between the best and the worst performance. In the lower-left corner, important information is available regarding the operation of the generating units.

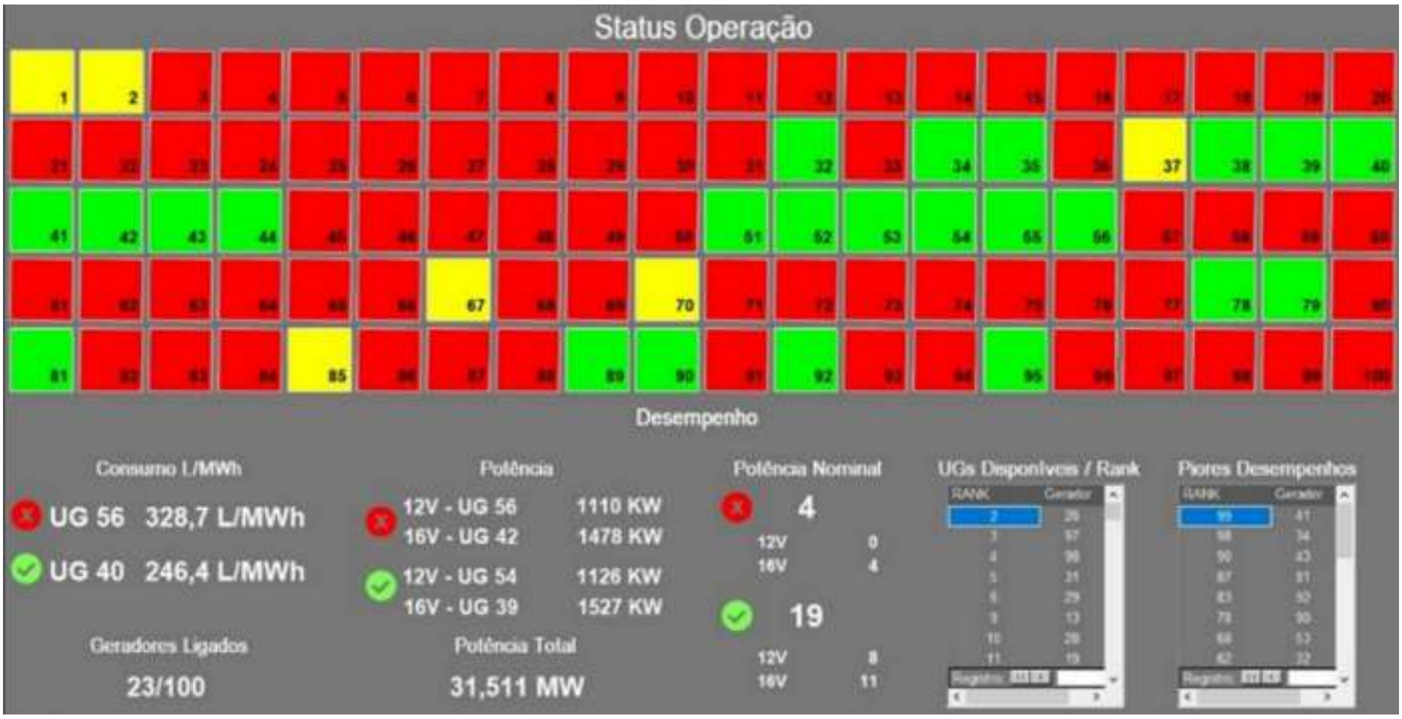


Figure 4. Supervisory system home screen (in Portuguese).

Presentation of the developed network

This section presents some details of the developed network addressing topics such as linking the database with master CLP, WebServer link with master PLC, slave PLCs, and general network topology.

SQL Execution on the Master PLC Ladder

SQL execution on the master PLC ladder occurs with the control program activating ModBus communication and activating the internal contact that makes the first SQL recording. If the database server is not active, a constant pulse restarts the recording process until it gets a positive response from the recording.

After the 1-second pulse flag is activated, the SQL execution block is updated with the first generator unit's information. Suppose the recording occurs and there is no error in the SQL execution on the database server. In that case, the contact that acts on a new SQL execution block is active but with the second generator unit's information. If a recording error occurs, an error contact is activated to demonstrate this failure. This process repeats for all generating units, restarting the cycle after that, in the first generator unit. Figure 5 shows the process of the SQL execution on the database server pictorially.

Integration between the Master PLC and the Web Server System

The master PLC developed has an integrated WebServer, which allows the user to verify the following information: (a) state of communication between the Master PLC and each of the slave CLPs; (b) state of CAN communication of each of the slave CLPs; (c) SQL recording state in each of the tables in the database; and (d) data from each of the generators, including values involved in the process, inputs and outputs, including alarms.

The Web Server interfaces are written in Portuguese (native language in Brazil); however, some names are written in English due to the operators' use. This fact occurs with the parameter names and alarm names, as shown in Figure 6, where some operator's screens appear. In both screens, the operator can select the parameters to be displayed, and also, he/she can choose which alarms must be activated to each unit (in the case, unit#1).

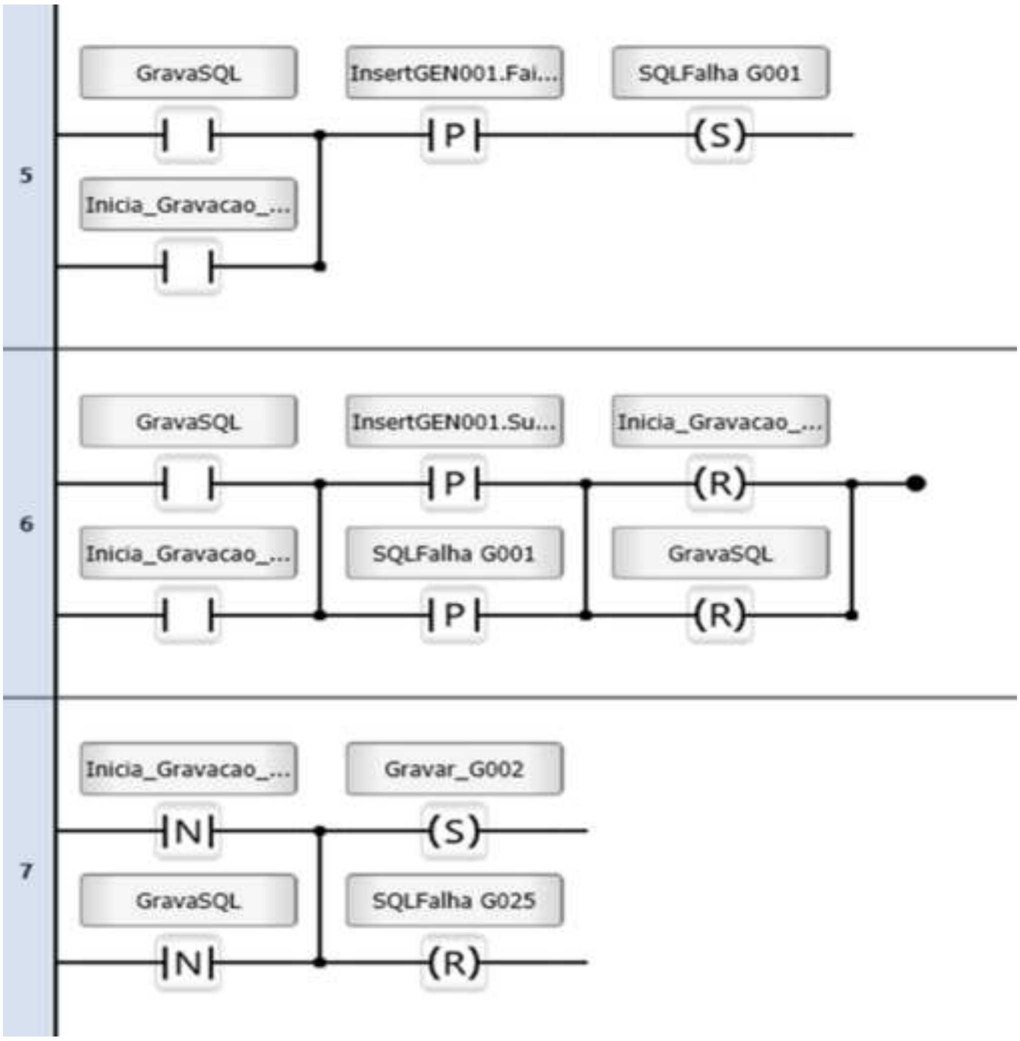


Figure 5. Process of checking for errors in SQL execution on the database server.

Integration between Slave PLCs and Network Topology

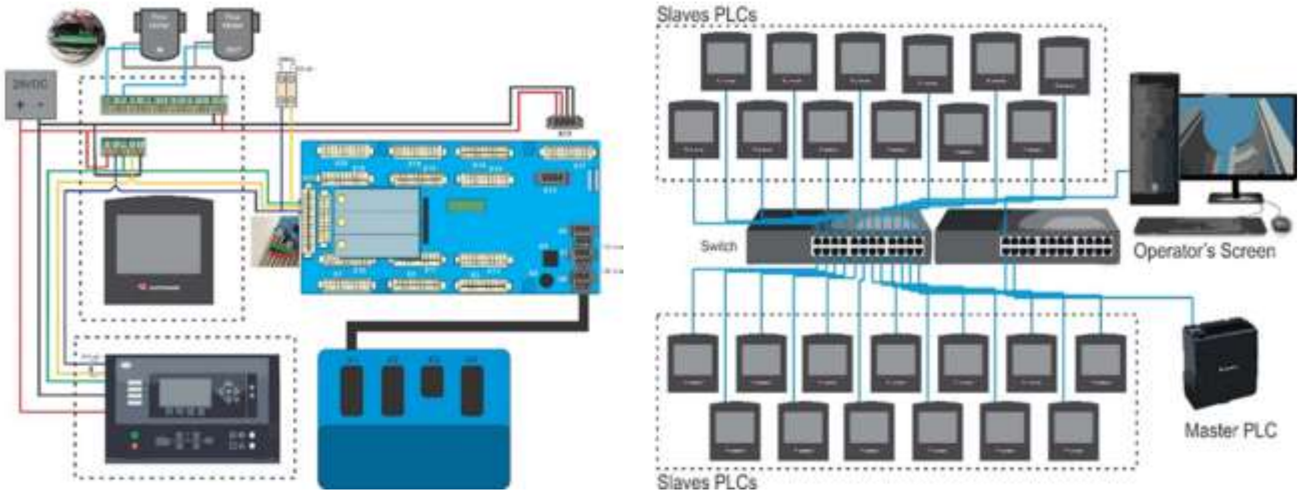
Slave PLCs are connected to the existing CAN-Open network on each of the generators. The diagram of Figure 7(a) exemplifies this link. In this topology, the slave PLC is inserted into the existing CAN-Open network, making it another node. For this installation, it was necessary to look after the two resistors of 120 ohms at the beginning and end of the network. The CAN-H and CAN-L order was respected at the time of connection.

The flow meters are connected in the first two channels of fast inputs of the PLC, and in the first channel (slot 15 of the input station), the blue wire of the input meter was connected. The second channel (slot 13 of the input station) was connected to the output meter's blue wire. Each of the meters' brown wires was connected to a 24 VDC power supply's positive pole. The PLC must also be connected to a 24 VDC power supply, with the positive pole in slot 1 and negative in input slot 2.

All equipment involved in this solution has been integrated into the form shown in Figure 7(b). This figure shows the slave nodes, the master PLC, and the computer must be connected to the two HP port switches pictorially. These switches and the master PLC were installed in the Palmeiras de Goias Thermal Power Plant rack. A 24 VDC power supply powered the master PLC.

(a) (b)

Figure 6. Examples of operator's screens related to the generator unit #1: (a) parameter screen and (b) alarm screen.



(a) (b)

Figure 7. Topology: (a) integration between slave PLCs, and (b) final network installed at the Palmeiras de Goias Thermal Power Plant.

Analysis strategy

The computational strategy of control and analysis developed is based on a hybrid system that merges intelligent systems, mathematical functions, and statistical functions. Among other system functions, this strategy is responsible for creating a ranking and diagnosing the generators. In this system, the variables are obtained through the sensing system, and the computational strategy should allow the manipulation of the parameters according to the operator's decision-making needs.

Variables of a distinct nature model the generation unit. Thus, several analysis profiles appear. One focused on generating the unit's consumption, and the other more focused on the coolant's temperature or even in the hours of operation that the generation unit is working. The latter is also used to balance the weight of each parameter according to the selected profile.

The level of importance between variables is not easily determined analytically. Therefore, one of the proposals of this implementation was to find a mathematical tool that would allow an objective comparison, even if not analytical, between the levels of importance, increasing them according to their respective quantities to construct the ranking of the dispatching of the generating units. Several techniques and methodologies were tested, and the Analytic Hierarchy Process (AHP) [9, 10] was chosen for its flexibility in the processing of data and measurements and the possibility of incorporating information from the operators or technical staff of the plant. In this development, the traditional AHP was modified, and a new type of procedure has been implemented, generating the Modified Analytic Hierarchy Process (MAHP).

Theoretical Foundation

The AHP method can be understood more easily through analogies with the organizational structure of the human mind. The tool developed by Saaty [9], which received increments posteriorly [11 - 14], has contributed significantly to the evaluation and classification of countless situations.

When faced with many elements, controllable or not, that cover a complex situation, the mind aggregates them into groups, according to some common properties. The model of this brain function allows repetition of the process at different hierarchical levels. It is based on common properties to identify the elements. These are grouped into a new set of properties, creating elements belonging to another higher level until it reaches a single maximum element, which is identified as the purpose of the decision-making process.

The method divides the problem into hierarchical levels clearly by summing up the values of decision agents. As a result, a global measure is assigned for each of the alternatives, prioritizing them or classifying them at the end of the procedure.

Foundations of the Proposed Methodology

The procedure used by the Modified AHP (MAHP) method can be divided into two steps: hierarchical structuring of the decision problem and functioning of the method. The decision-making element must structure the problem. For this, the criteria are combined according to the various hierarchical levels necessary, which results in a more faithful representation of the problem. The relevant alternatives are also studied given each criterion of the lowest hierarchical level. However, this structure should have a high degree of detail since the criteria applied at each level must be homogeneous and non-redundant [10].

The interface is composed of text fields, in which the priorities of each variable are displayed in addition to the degree of inconsistency. When one tab is chosen, the sliding controls show up on the screen. These controls are responsible for the parity comparisons for the alternatives for a given criterium or between the criteria.

In the classical AHP, the alternatives are treated by each criterium, creating a matrix where the alternatives are comparing pair-to-pair. In this case, if n criteria and m alternatives exist, a set of n matrices with mxm size are built. After that, there are two possible ways to merge the information of these matrices. One is combining these n matrices through pair-to-pair comparisons, obtaining a final matrix, and then computing the final matrix's eigenvector. The other way is computing the eigenvector of each n matrices and then merging the n eigenvectors by a predefined matrix with each criterium's importance. In both cases, the number of arithmetical operations for real-time, with many criteria and alternatives, is enormous. Consider the case treated in this development, where exist 9 criteria and 99 alternatives. Nine matrices 99x99 are built; imagine the computational effort to combine pair-to-pair and after computing the eigenvectors.

In the proposed MAHP, the criteria are treated independently of the alternatives. The criteria are established, and only a single matrix is created. In our example, a matrix nxn. This matrix uses a similar Saaty's scale, named fundamental scale, presented in Table 1. The parity comparison is performed using this scale that ranges from 1 to 9 and their inverse values (1 to 1/9). Each value in Table I has a linguistic meaning. For instance, if an alternative A has a 'relative importance' than an alternative B, its value of the comparison is 3. And the comparison between B and A is 1/3. Intermediary values, like 2, 4, 6, and 8, can also be used.

Table 1. Fundamental Scale.

Value	Linguistic Meaning
1	Same importance
1/3 or 3	Relative importance
1/5 or 5	Medium importance
1/7 or 7	Robust importance
1/9 or 9	Strong importance

Continuing the example, the user may define a different value of the relation between B and A than 1/3. In this case, inconsistency is introduced in the matrix. It is possible, and the degree of consistency (named consistency ratio) is computed as shown in [11]. This degree's recommended acceptable levels are 10%.

After constructing the criteria matrix, its eigenvector must be computed. In our case, the power method was used due to the size of the matrix. This method is shown below. This eigenvector (1xn size) will use in the final part of the MAHP.

In the actual implementation, the engineers made the above part of the MAHP in the pre-operation phase. Where some criteria of energy production are defined, and each criterium has an own eigenvector. A set of eigenvectors (1x9 size) will be available to the operator to establish the production ranking according to a given criterium. Also, the developed software presents the value of the consistency ratio during the formation of the criteria matrix.

The second part of the MAHP is the construction of the alternative matrix. This matrix has nxm size, containing information related to each (n) criterium for each (m) alternative. In our case, the alternatives are the generating units, and this matrix is automatically composed of information that came from the database each minute. This part of MAHP is performed in the control center.

The final step of the MAHP is to produce the answer. It is made by the product of the eigenvector (1xn size) resulted from the criteria matrix and the alternative matrix (nxm size), resulting in a vector (1xm size) with values for each alternative. In our case, the final step is performed when the operator needs to increase (or decrease) the generation of energy produced by the power plant. At this moment, the computational program takes the selected eigenvector and multiples for the alternative matrix, composing the final vector with the score for each generating unit. All this process is entirely transparent for the operator. For him/her, it is shown only a list of the best generating units to be operated.

Foundations of the Proposed Methodology

After the construction of the criteria matrix (nxn size), for n criteria. It is necessary to compute the eigenvector of this matrix. Many methods could be used. In this development, the Power Method was implemented due to its good performance and fast convergence or the typical parameters used in this problem.

Let us a matrix A (nxn size), the criteria matrix, and an auxiliary vector b (1xn size). Let us also a subscript k being an iteration indicator. First, the process initializes the vector b with random values, but usually, each element is filled with the value 1/n. Equation (1) shows how to compute the next iteration of the vector b. First, multiply A by bk and then divide the result by the module of the same result previously obtained. The process is repeated until the error's value is within a predetermined threshold or the maximum number of iterations has reached.

$$b_{k+1} = \frac{(A * b_k)}{\|A * b_k\|} \quad (1)$$

Presentation of the computational tool

After presenting the mathematical technique, which supports this development, this section illustrates how it was integrated into the decision-making process and its relationship with the database. Access to data related to ranking, alarm indicators, and diagnostics of generating units is performed through a computational tool. The Python programming language was used in this implementation by the ease of integration with the SQL language and with the equipment of the developed network. A set of screens for human interfaces (all in Portuguese) were developed for this purpose.

The set of variables collected by the sensing system is used as a criterion. These 9 variables (criteria) are:

(1) the time that the liquid of the intercooler spends above the average,
(2) the time that the coolant spends above average,
(3) the hour-meter,
(4) numbers of failures,
(5) the time with the load between 50% and 60%,
(6) the time with the load between 60% and 73%,
(7) the time with the load above 73%,
(8) fuel consumption at start-up, and
(9) power in kVA generated.

Part of the values used in the ranks' composition is constructed from data coming from a table in CSV files, which are composed of historical data.

The computation of generator unit scores is automatic and based on repetition cycles that run through generating unit per generating unit and, in each cycle, some steps are completed. Before starting the mentioned steps, it is necessary to check if any generating unit is in operation at the time of computation. This information can be found in the Boolean variables table, i.e., the operating state is monitored by 1 (generator unit on) or 0 (generating unit off). If no unit is in operation, calculations are not performed. After the scan is completed, the first step is to access the database to get the tables and instant data from the respective generator. These are saved in vectors to be used in the rest of the algorithm.

After importing the information from the database, the historical data stored in the CSV table is also imported to vectors and used by the Python software. The variables that are stored in the CSV file are the indexes of the generator units, the average coolant temperature, the time the coolant stays above the average, the average temperature of the intercooler liquid, the accumulated amount of time the intercooler liquid remained above the average, the average oil temperature, the accumulated amount of time the oil stayed above the average, the number of times the generator had to be started-up, the accumulated amount of time the generator stayed with the load below 60%, the accumulated amount of time the generator stayed with the load below of 73% and above 60%, the accumulated amount of time that the generator had the load between 100% and 73%, the fuel consumption at the start, the number of samples and, finally, the timestamp at the moment the sampling occurred.

With the merger of the historical data and database numbers, the criteria variables' new values will be recalculated. The calculation of fuel consumption will start with a vector with 10 empty spaces, in which the last 10 KVA power reads will be stored. If this vector's differentiation has positive values greater than 150, it indicates a start-up, while the negative values indicate a small voltage drop after starting.

If the vector has in its first positions power values equivalent to 0, it is possible to find the start-up instant for the generator. Consequently, in possession of these instants, there is the possibility to calculate fuel consumption in this period. After that, the amount of time that the intercooler, coolant, and oil liquids were above average is calculated. First, it is checked whether the temperature is above average; if it is, the difference between the previous and the current time marker is calculated. This difference is added to the value of the variable responsible for storing the time values. This process is like determining how long the generator is in a set of values for the load. One of the existing conditions compares in which range the load variable is located. If it is in one of these ranges, the duration of the time is added.

Another procedure in this algorithm is the calculation of the number of new start-ups. A new start-up should occur when a generator has its power generation interrupted, often unwantedly, for a time considered short. After this period, start-up occurs, in which it reconnects the generating unit to the system, returning to its normal operating conditions. In this work, the new start-ups of the generating units are expected to happen within a maximum of 10 minutes. Like the algorithm for determining fuel consumption at the start, the process for finding the number of new start-ups will begin by differentiating a 10-position vector. These are filled with the kVA values for each generator. The powers occupy the indexes of this vector's positions, respecting the previously defined conditions, i.e., they can assume values in kVA equal to zero and differentiation greater than 150.

If the algorithm finds more than two indexes for the conditions mentioned above, the last and the penultimate index will be chosen. They are called the Start Indices. The algorithm also generates a vector with the previous 10-time markers of predominant importance in determining the number of new start-ups. From the Start Indices, the time markers allocated in their respective positions were obtained. Thus, the time variation between the supposed shutdown and restart is defined. Therefore, to be considered as a restart, it is necessary to check if this variation in time is less than or equal to 10 minutes. If it is less than or equal, increase the variable that counts the new start-ups.

Throughout the algorithm's processing, the priority vector is updated with values from the parity comparisons in the software interface with the sliders. Before using the vector to determine the final score, some of the vector elements will be multiplied by -1, making them a negative value, better reflect the variables that positively or negatively impact the generator's operation, and avoid extrapolation of values during data processing. So, it is essential to keep in mind that the more negative the score, the worse the generators' performance. This excess of extrapolation can happen when multiplying the priority vector and the parameters of the selected generating units is very high.

After all these calculations, the rankings will be constructed through the vector multiplication of the priority vector and the generator variables. The classification will update a spreadsheet in the database with the instantaneous values. Another table must also be updated to control each generating unit's minimum, maximum, and current ranks. And the generator variables will be saved again in the CSV file, keeping it continuously updated.

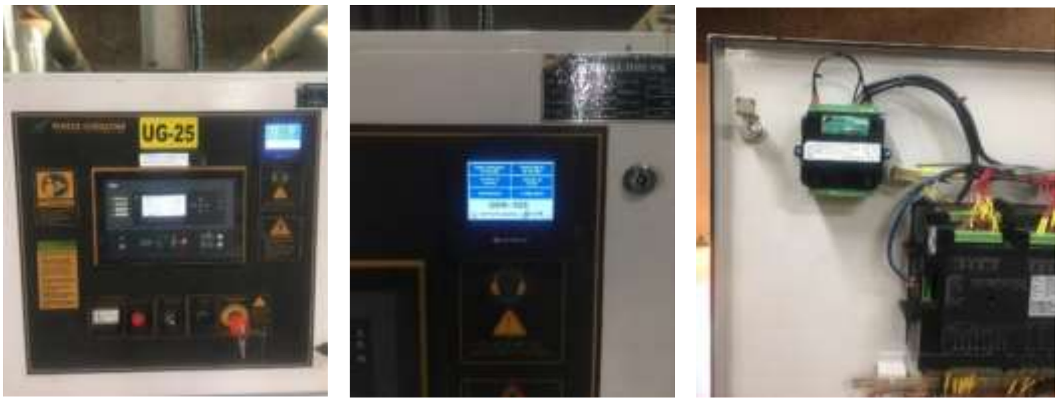
RESULTS

In this section, qualitative analysis for the data originated from 99 generating units located in Palmeiras de Goiás Thermal Power Plant in Brazil's central-western region. Figure 8 shows some of the 99 generating units.

Details of the Implementation

After the total installation of the infrastructure (CLPs, switches, flow meters, cables, and so on), all components were tested and accessed remotely. Everything is fully functioning. For example, in Figure 9, some pictures of this installation for generating unit #25 (named GEN-025) are shown.

Figure 8. Part of the 99 generating units of the Palmeiras de Goias Thermal Power Plant.



(a) (b) (c)

Figure 9. PLC operating in the panel of the generating unit #25: (a) general panel of unit #25, (b) new display included in this development, and (c) connections of the slave CLP.

The concentrator PLC was installed next to the panel in the control room. Its communication functions in the industrial network were confirmed based on access to the PLC's web browser. Figure 10 shows a picture of the PLC hub web browser access.

A reformulation of the supervisory system's screen system was necessary, including the visual adaptation of the home screen to the visual standards of the main supervisory of Palmeiras de Goias Thermal Power Plant. A new adaptive screen has been developed, displayed on the second monitor, which shows each selected generator's information on the main screen, including graphs with historical values. Figure 11(a) shows all the final supervisory system screens, the two screens on the left are the new supervisory system screens. These screens are presented in detail in Figure 11(b).

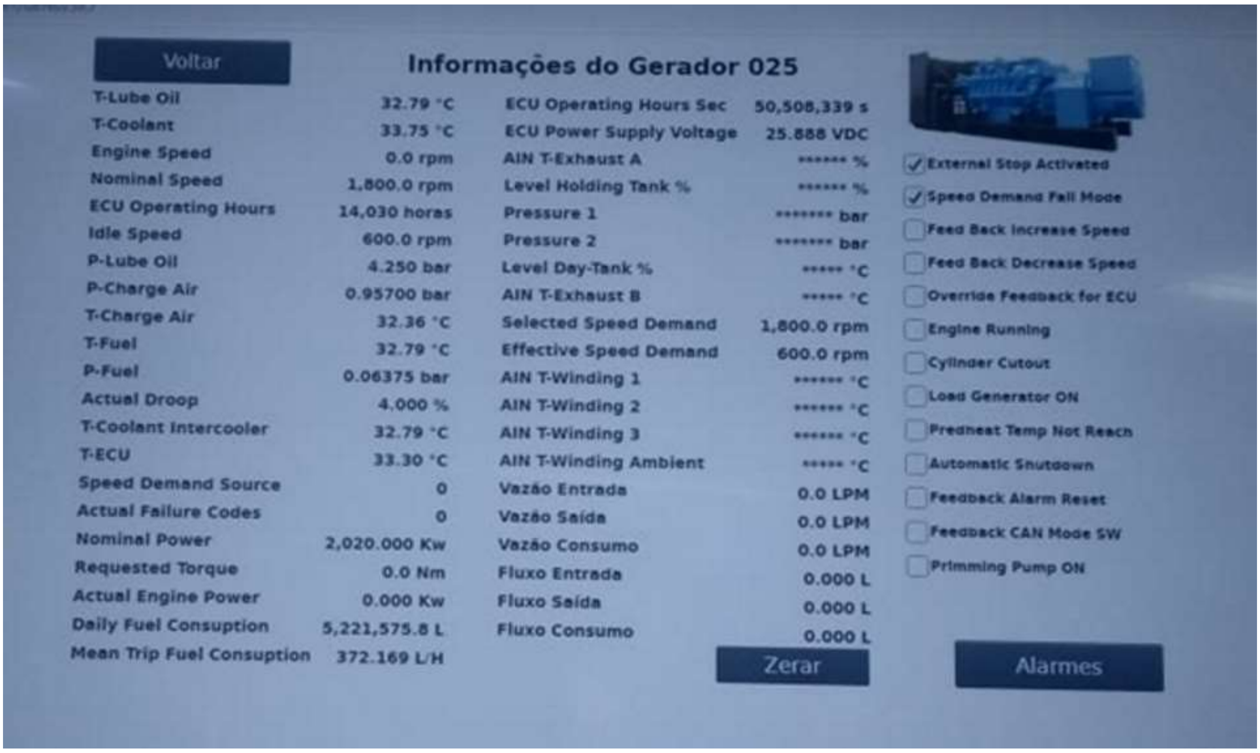
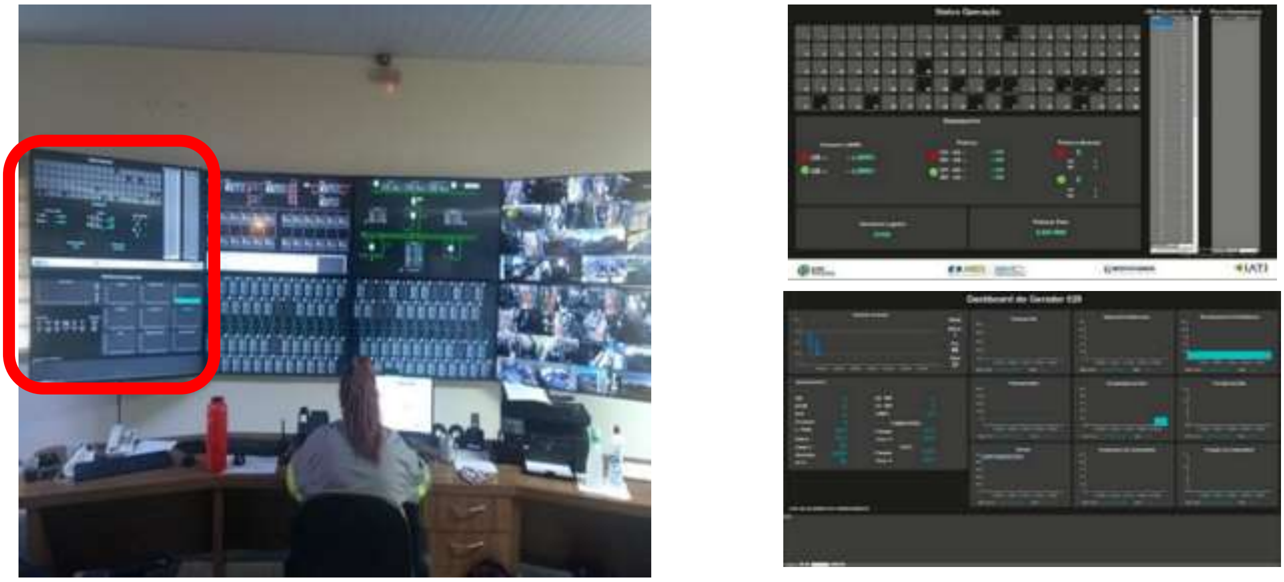


Figure 10. Picture of a PLC hub web browser access screen of unit #25.



(a) (b)

Figure 11. Supervisory system: (a) screens installed, and (b) new supervisory screens in the control room of Palmeiras de Goiás Thermal Power Plant.

Technical Results of the Implementation

The generating units were classified and ranked within three different scenarios. The three scenarios used the proposed MAHP to determine the generating units' classification, with only the weights given for each variable different from each one. The first scenario proposes that all variables have the same weight. The second scenario considers prioritizing the variable that indicates the amount of time with the load above 73%. Finally, the third scenario has fuel consumption with the highest weight. The criteria matrix for the first scenario has the value 1 in all positions of the matrix. In the second scenario, line 7 presents the value 9, and column 7 shows the value 1/9. In position (7,7), the value is 1. Because the criterium “the amount of time with the load above 73%" is the 7th criterium. All other elements of the matrix are like 1. Finally, in the third scenario, the same occurs in line and column 8, related to the "fuel consumption." Table 2 shows the eigenvector produced in each test.

Table 3 presents the results for the three scenarios showing the best five generating units. The operator can access a complete list of results. Figure 12 shows the completed list of results for the first scenario, with each generating unit's score. It is possible to observe the result of the best unit, number #82, has almost the same score as the second-place unit, number #83; while the third, fourth, and fifth position units, number #46, #66, and #7, respectively, have lower scores. In this scenario, the worst unit to start is the number #84. The operator can also demand to show this figure before he/she takes the necessary action.

Table 2. Eigenvector Produced in each Test.

Criteria	First Scenario	Second Scenario	Third Scenario
(1)	-0.1	-0.0556	-0,0556
(2)	-0.1	-0.0556	-0,0556
(3)	-0.1	-0.0556	-0,0556
(4)	-0.1	-0.0556	-0,0556
(5)	-0.1	-0.0556	-0,0556
(6)	-0.1	-0.0556	-0,0556
(7)	-0.1	0,5	-0,0556
(8)	-0.1	-0,0556	0.5
(9)	-0.1	-0,0556	-0,0556

Table 3. Eigenvector Produced in each Test.

Ranking	First Scenario	Second Scenario	Third Scenario
1st	82	82	83
2nd	83	83	82
3rd	46	46	46
4th	66	66	66
5th	7	7	7
⋮	⋮	⋮	⋮
Worst	84	89	84

Other screens were also produced to give support to the operator to take his/her decision. Each generating unit has its own window with all available information. Observing this window, the operator can check all the generator variables to determine a possible problem or to verify an alarm. Figure 13 shows the information related to generating unit #52. In the upper-left part of the window, the ranking history of this generator is shown. Also, the screen data indicates that the processed data was correctly recorded in the database and that the supervisor system can interpret the variables coming from the data concentrator PLC.

Also, this individual screen for each generating unit verifies the reasons for poor scores and bad positions in the ranking. Checking these screens, the operator can observe that some machines could be running with higher consumption than the other generators. With this information, the operator can identify and mitigate any unsatisfactory state for the generators.

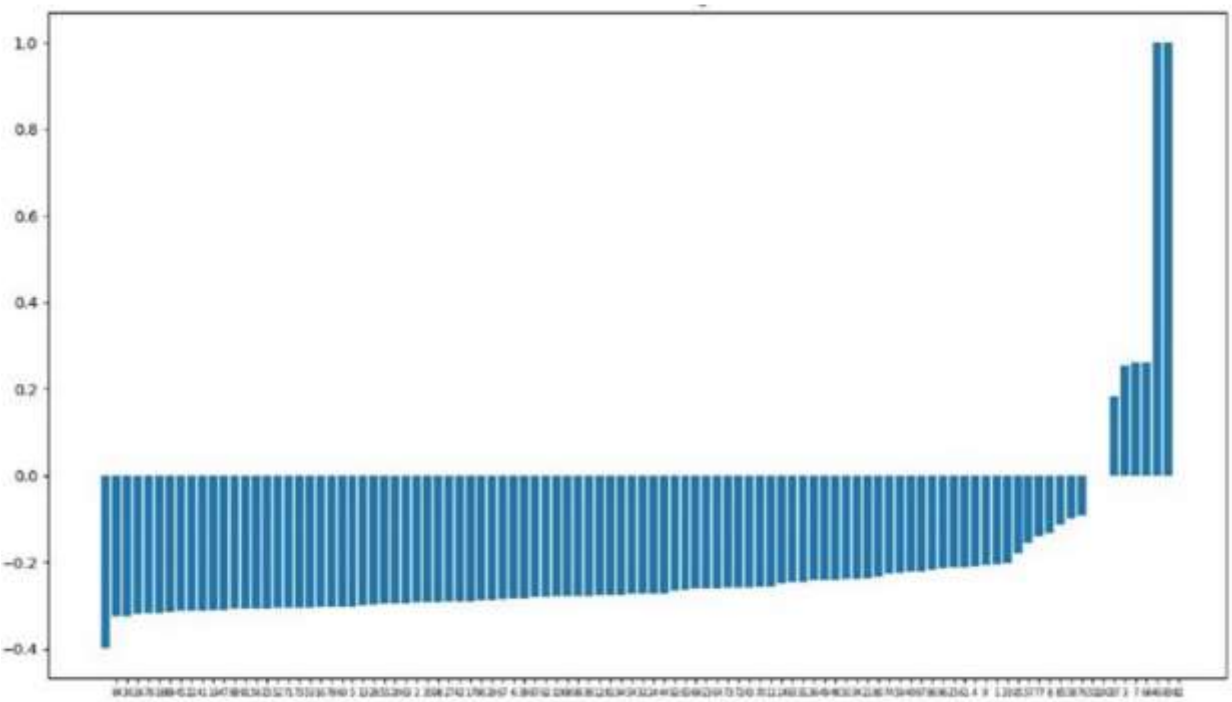


Figure 12. Scores of all generating units for the first scenario.

Figure 13. Dashboard of the unit #52 (in Portuguese).

CONCLUSIONS

The paper presents a control and monitoring solution for a thermoelectric plant. The solution facilitates the diagnosis of the generating units, supports their start-up, and monitors the variables pertinent to the generators' operation.

The procedure used was based on implementing more sensors to improve the measures' accuracy and integrate the existing system used on the generator units to the newly developed supervisory. A data transmission network was created, allowing the storage of variables in the database. Besides, it was necessary to create a computational tool capable of performing all possible calculations with the data presented.

The developed structure allows checking in real-time the conditions for the 99 generators of a thermoelectric plant. Thus, it was possible to perform the ranking of these machines through variables representative of the operation. For that, an approach, named Modified Analytic Hierarchy Process (MAHP), was proposed and implemented to treat a large number of variables that came from the 99 generating units and combine with several scenarios of production of energy. The MAHP is fast enough to provide a ranking of generating units in real-time. Furthermore, it enabled the operator to view the variables of interest in an integrated supervisor system.

This set of solutions brought more quickness to the process of repairing generators. It also facilitates identifying possible problems in the process, increases reliability, and brings more safety to the plant's operation. In this way, it allows quickly and reliably that all variables are continuously monitored. The system is currently operating at the Palmeiras de Goiás Thermal Power Plant.

Funding: This research was funded by CEPASA Power Plant, Hidrotermica Group, inside the ANEEL R&D projects.
Acknowledgments: The authors would like to express their thanks to CNPq, and CAPES.
Conflicts of Interest: The authors declare no conflict of interest.

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